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Structural Behavior of Masonry Walls Built with Bricks Manufactured with Geopolymer Concrete under Vertical Load

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Abstract

The use of cement bricks in construction projects has raised concerns about the environmental impact of cement production. The production of 1000 bricks consumes 8 - 10 cement bags. To address these concerns, Geopolymer bricks have emerged as a more sustainable alternative for its eco-friendliness. The current study is a comprehensive study conducted to evaluate the structural performance of Geopolymer bricks compared to cement bricks walls and prisms. The study included comparisons between mode of failure, ultimate capacity and load-strain relationships of walls with and without openings. The researcher manufactured the cement and Geopolymer bricks used in the current study at a brick factory in the tenth of Ramadan city in Egypt. Moreover, Geopolymer mortar was used to build the Geopolymer bricks walls and prisms. The experimental program consisted of six walls were constructed; three walls were constructed using Geopolymer bricks, while the other three walls were made of cement bricks. Each type of brick included a solid wall, a wall with a door opening and a wall with a window opening. The production of Geopolymer bricks, as an alternative to cement bricks, offers several advantages; Geopolymer bricks were stronger by 21.76% than cement bricks. In addition, Geopolymer mortar can use as a substitute for cement mortar. Additionally, solids wall made of Geopolymer bricks were stronger than 15.38% those made of cement bricks. Contrary, Geopolymer brick walls and prisms showed lower initial stiffness than the corresponding cement brick walls and prisms.

Key Words: cement bricks, Geopolymer mortar, Geopolymer concrete bricks, prisms, walls.

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1. Background

S.B. Singh (2017) and N. Sathiparan et al. (2018) brick masonry is a highly popular building material worldwide, particularly in developing countries, due to several advantages. These include the easy availability of its constituent materials, convenient handling, effective heat and sound insulation, especially for hollow unit's impressive compressive strength, and cost-effective construction methods [1, 2]. P. Murthi (2021) brick masonry buildings make up 62.38% [3] S. Elavarasan (2021) of the total buildings in Pakistan, while brick, block, and stone masonry account for 74.25% of the country's built environment [4]. C.K. Gupta the demand for brick masonry buildings is steadily rising due to population growth and the ongoing rural-to-urban migration trend. These conventional structures primarily comprise two essential materials: burnt clay bricks, cement bricks and traditional mortar [5]. T. Akram (2009) in brick masonry construction, conventional mortar typically utilizes ordinary Portland cement (OPC) as a binder. However, the use of cement in construction contributes to CO2 emissions. Approximately 0.8-1.0 ton of CO_2 is released into the atmosphere for every 1.0-ton production of ordinary Portland cement. This accounts for 5-8% of global emissions, resulting in significant environmental impact. To mitigate this, the use of pozzolanic materials as partial cement replacements in concrete or mortar can be employed [6]. Additionally, due to the hydration process of cement in the masonry mortar, the formation of a weakened layer of calcium hydroxide or Portlandite (CH) at the interface between the brick and mortar may occurred [7]. R. Siddique (2009) these reactions lead to the formation of compounds with cementitious properties, which ultimately improve the properties of mortar and masonry [7]. R. Siddique (2009) the use of pozzolanic materials in the mortar, not only can reduce cement consumption and conserve the environment, but it can also effectively enhance the bond strength of masonry. This enhancement is achieved through the production of a strong calcium silicate hydrate (CSH) gel, resulting from the reaction between the pozzolanic materials and weak calcium hydroxide (CH) crystals [7]. Lahiba Imtiaz (2020) on the other hand, Geopolymer concrete bricks are an innovative and sustainable alternative to traditional cement bricks, made primarily from industrial by-products like fly ash and slag, activated with alkaline solutions. These bricks offer significant environmental benefits, including a lower carbon footprint due to reduced CO_2 emissions during production compared to ordinary Portland cement. Additionally, they utilize waste materials, promoting recycling and minimizing landfill use. To enhance their economic viability and environmental friendliness, strategies such as optimizing raw material combinations, scaling production, and increasing awareness among builders and consumers can be implemented. A research indicated that Geopolymer bricks not only provide a durable construction material but also contribute to sustainable building practices, making them a promising solution for the future of construction [8]. Anass Harmal (2023) Mechanical

Properties: Geopolymer bricks exhibit comparable mechanical properties to traditional bricks, with added benefits of greater durability and resistance to environmental degradation. This makes them suitable for various construction applications, including non-load-bearing walls. Experimental Studies: Recent experimental studies have focused on the characteristics of Geopolymer-stabilized compressed earth bricks, highlighting their potential in sustainable masonry construction. These studies aim to refine the production techniques and improve the performance of Geopolymer bricks [9].

2.Experimental program

1.1 Introduction

The current experimental program included manufacturing cement and Geopolymer mixtures of Geopolymer concrete bricks. Four mixtures of Geopolymer a concrete brick was made at a brick factory in 10th of Ramadan City, to get the best mix, which was used in building the Geopolymer concrete brick walls and prisms. Six cement and Geopolymer concrete brick walls and four shapes of prisms were built and tested as illustrated below.

1.2 Properties of used materials

2.2.1 Ground granulated blast slag (GGBS)

In the present study, GGBS is used as a pozzolanic material to make Geopolymer mortar and concrete. It was ground internally and manufactured according to cement specifications in terms of, quality and fineness before being packed into ready-made bags. The results of chemical analysis are shown in Table (1).

Table 1: Chemical analysis of GGBS element.

Name	%
Silicon dioxide (SiO_2)	36.60
Aluminum oxide(Al2O_3)	12.6
Ferric oxide (Fe_2O_3)	.98
Calcium oxide (CaO)	37.40
Magnesium oxide (Mgo)	5.62
Sodium oxide (Na_2O)	.32
Potassium oxide (K_2O)	.89
Titanium dioxide (TiO_2)	1.85
Manganese(II) oxide (MnO)	1.56
Ceric oxide (CeO_2)	.2
Barium oxide(Bao)	.16
Zirconium dioxide (ZrO_2)	.05
Phosphorus pentoxide(P_2O_5)	.02
Nickel oxide (NiO)	.02
Chlorine (CI-)	.05
Loss on Ignition (LOI**)	.03
Total	99.98

2.2.2 Alkaline liquid (Activator)

The alkaline liquid used in the current research as an activator to react with the pozzolanic materials was a mixture of sodium silicate solution (Na_2SiO_3) and sodium hydroxide solution (NaOH). Sodium-based solutions were chosen for their cost-effectiveness compared to potassium-based solutions. The Na_2SiO_3 solution, commonly known as was obtained in liquid from the market. It had a composition of 0.45 solids (Na_2O + SiO_2) and 0.55 water, with a specific gravity of 1.6 according to the manufacturer's data sheet. Sodium hydroxide (NaOH) was obtained in flake form from the market, with a purity of 98% and a specific gravity of 1.47. It was then converted into a solution by mixing it with water to achieve a molarity of 10 M and 12 M. However, the literature suggests a range of NaOH solution molarities from 6 M to 14, therefore 10 M and 12 M were selected for the current study.

2.2.3 Fine aggregate

Sand is commonly used in the production of mortar and concrete. The characteristics of the sand used in this study meet the requirements specified in the Egyptian standard specification for sand is ES 1109/2021 [10].

2.2.4 Coarse aggregate

In the current study, crushed stone made of dolomite was used as a coarse aggregate. This type of crushed stone is locally available in Egypt and specifically sourced from Atoka, El Suez. Testing of the coarse aggregates was conducted in accordance with the Egyptian standard specification number for coarse aggregate is ES 1109/2021[10]. The physical and mechanical properties of the used coarse aggregate were evaluated.

2.2.5 Water

In the experimental program, clean tap water, suitable for drinking, was used. This water was utilized for preparing the sodium hydroxide solution for Geopolymer mortar and bricks. Additionally, it was added to all mixtures in the experimental program. The purpose of adding water to the mixtures was to achieve a homogeneous and workable mixture.

2.2.6 Cement

The ordinary Portland cement (OPC) used in this research was produced by Helwan cement company, CEM I 42.5 N. It was utilized to produce all the control mixtures in the present study. The specifications of the Egyptian standards (E.S.S. 4756-1/2018) [11] were met by the used cement.

2.3. Design of concrete mixtures for brick industry

Four Geopolymer mixtures are manufactured for the production of Geopolymer bricks and one mix for cement bricks. The bricks were manufactured in the brick factory in 10th of Ramadan City. Two of the Geopolymer mixtures were with a content of 350 kg/m^3 and concentrations of 10 M and 12 M of sodium hydroxide (NaOH) solution, respectively. The other two mixtures have a content of 450 kg/m^3 and concentrations of 10 M and 12 M of sodium hydroxide solution. The ratio of coarse to fine aggregate were about (1:1.5) and the ratio of sodium hydroxide to sodium silicate were (1:2.5). On the other hand, the total water to total solids in the mixtures was 0.40. By knowing the specific gravity of each material, absolute volume equation can use to determine the quantities of all mixtures of Geopolymer concrete as shown in Table (2). Only one cement mixture with a content of 450 kg/m^3 manufactured with water-cement ratio equals 0.40, as shown in Table (3).

Table 2: Quantities of Geopolymer concrete mixes (GPC mixes) for Geopolymer concrete bricks

Component/ mix No (kg/m^3)	**Mix (1)**	**Mix (2)**	**Mix (3)**	**Mix (4)**
GGBS	350	350	450	450
Fine aggregate	733	715	647.6	616.3
Coarse aggregate	1100	1072.5	971.5	924.5
Na2SiO3 solution	100	100	128.5	128.5
NaOH solution	40	40	51.5	51.5
Extra water	85.6	103.8	108.9	133.7
Molarity (M)	10	12	10	12
Total water /total solids	0.40			

Table 3: Quantities of the cement concrete mix (OPC mix) for cement bricks

Component/name	**Cement mix(kg/m^3)**
Cement	450
Fine aggregate	717
Coarse aggregate	1076
Water	180
W/C ratio	0.40

2.4 Manufacturing process of bricks

At Al-Read factory in the 10th of Ramadan, which is a semi-automatic bricks factory, see Figure (1), one production line of the factory was dedicated for manufacturing the Geopolymer bricks. Previous research indicated that the best time to prepare the alkaline solution is the day before pouring because of preparing the sodium hydroxide solution produces a lot of heat. The prepared sodium hydroxide solution and the sodium silicate solution were combined until the desired solution attained uniformity. Until the casting day, the alkaline solution should be kept at room temperature for a full day. On the casting day, the following steps were taken to prepare the Geopolymer concrete:

- Gradually adding the slag to the fine and coarse aggregates and mixes them for a minute using the mixer.
- Adding the liquid alkaline solutions and half of the extra water, mix them for other three minutes.
- The last half of the extra water was added to the mixture and stirred for other three minutes to obtain a homogeneous mixture. On the other hand, the mixing process for standard Portland cement formulations was carried out in the same manner as for ordinary cement bricks. The mixtures were cast in the bricks molds and then vibrated and compacted by the hydraulic pressure compactor. The bricks were keeping for curing in places beside the mixer. After the first 24 hours, the Geopolymer bricks were stored in black nylon bags. The bricks were keeping in a controlled environment within the factory for a period of 7 days to allow for adequate curing. On the other hand, after the initial 24 hours, the cement bricks were cured by spraying them with water for a duration of additional 7 days to ensure complete hydration and strength.

Fig. 1: Production line of Al-Raed Factory, 10th of Ramadan.

Fig. 2: Cement and Geopolymer bricks after casting.

Fig. 3: Curing of Geopolymer concrete bricks in nylon bags 24 hours after casting for 7 days.

2.5 Compressive strength of manufactured brick

Mixtures No. 1 and 3 (M=10) were chosen for making the brick specimens, while Mixtures 2 and 4 (M=12) were excluded because the mixtures were viscous and could not be formed in the molds of the brick machine. Table (4) shows the compressive strength results of bricks of Mixtures 1, 3, the cement mix after 28 days, and a comparison with the standard specifications ESS1292-1/2013 for bricks for load-bearing walls and non-load-bearing walls. It was noted that the results of mixture No. 3 was higher than the minimum required compressive strengths mentioned in E.S.S.1292-1/2013 i.e. Mix No. 3 complies with the Egyptian Standard Specification for bearing walls while results of Mix No. 1 didn’t comply with the Egyptian speciation for bearing walls, so the research will be completed and the walls and prisms will be built by bricks manufactured by this mix (3). On the other hand, cement bricks which manufactured by the mix mentioned in Table (3) were tested under compression and the results complied with the E.S.S .1292-1/2013 for load bearing walls, as shown in Table (4).

Table 4: Compressive strength of brick samples

samples	Dimensions (mm)	Minimum compressive strength (MPa)	Average compressive strength (MPa)	Minimum compressive strength (MPa) for load-bearing walls	Average compressive strength (MPa) for load-bearing walls	Minimum compressive strength (MPa) for non-load bearing walls	Average compressive strength (Mpa) for non-load bearing walls	Notes
GGBS (Brick samples) Mix (1)	250*120*60	7.5	12.19	7.5 < 11.7	12.2 < 13.1	7.5 > 3.5	12.1 > 4.1	can be used in non-bearing walls
GGBS (Brick samples) mix (3)	250*120*60	13.8	17.9	13.8 >11.7	17.9 > 13.1	13.8 > 3.5	17.9 > 4.1	can be used in load bearing walls
Cement Bricks mix	250*120*60	13.3	14.7	13.3>11.7	14.7>13.1	13.3>3.5	14.7>4.1	can be used in load bearing walls

2.6. Geopolymer mortar and cement mortar

Cement mortar ratios were taken according to the Egyptian building code ECP **203** – 2017 [12], while the ratios of Geopolymer mortar were taken similar to that of cement mortar, as possible. Table (5) mentioned the ratios of the ingredient to of used mortars.

Table 5: The mortar mixing ratios

Mortar Type	Cement Ratio	Slag Ratio	water Ratio	NaoH	Na_2So_3	Sand Ratio
Geopolymer mortar	0	1	.4	.11	.29	3
Cement mortar	1	0	.5	0	0	3

Cement and Geopolymer mortar poured into the designated molds to obtain the results of the compressive strength test as in Figure (4). The cement molds are keeping in the water basin until the day of crushing after 28 days.

Geopolymer mortar Cement mortar

Fig. 4: Cement and Geopolymer mortar in their molds.

2.7 prisms

Geopolymer concrete bricks of mix (3) and cement bricks were used to construct four models of prisms. Each model (shape) of prisms consisted of three identical Geopolymer concrete brick prisms and three identical cement brick prisms. It should be noted that Geopolymer mortar was used in the construction of the Geopolymer concrete brick prisms, while cement mortar was used in the construction of the cement brick prisms.

2.7.1 Prisms for in-plane splitting test

In-plane splitting strength is a measure of a material's ability to resist forces that cause it to expand or deform within its plane. Testing this property helps evaluate the ability of a material, such as brick, to resist deformation when forces are applied within its plane. This is crucial for determining the structural integrity of the material and its performance in various applications. As shown in Figure (5) for Geopolymer bricks and Figure (6) for cement bricks, the applied load was parallel to the bed joints mortar. The dimensions of the tested prisms were 500 mm height ×270 mm width. The Geopolymer prisms were P1 while the cement brick prisms named P2.

Fig. 5: Sample of Geopolymer prism (P1)

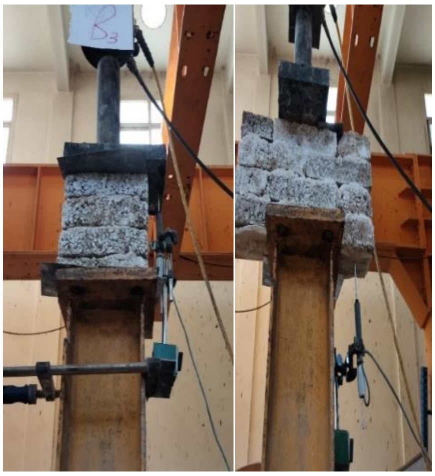
Fig. 6: Sample of cement prism (P2)

2.7.2 Prisms for axial compression test

Two sizes of prisms were tested under compression, one of dimensions 270 mm height ×250 mm width and named P3 for Geopolymer brick prisms and P4 for cement brick prisms while the other size with dimensions 270 mm height ×500 mm width and named P5 for Geopolymer prisms and P6 for cement brick prisms. This test involves applying a load on the length of the prism to evaluate its ability to withstand pressure. The prism was placed in a testing apparatus, and a compression load was applied vertically perpendicular to the mortar bed joints. The load was gradually increased until failure or reaching the maximum load-bearing capacity. During the test, load. vertical strain data was collected, see Figure (7)and Figure (8). The collected data were analyzed to evaluate the performance and behavior of the prism under axial compression. This information is essential for design considerations and the structural safety assessment of load bearing building elements. The Egyptian code for buildings ECP 144- 2009[12] mentioned that, prism compressive strength is one of the main items used for structural design.

(P3) **(P5)**

Fig. 7: Samples of Geopolymer prisms (P3, P5)



(P4) **(P6)**

Fig. 8: Samples of cement prisms (P4, P6)

2.7.3 Prisms for shear strength test

Shear testing is essential in various industries for determining the strength of different materials, such as metal, wood, polymers, and adhesives.: The data collected from shear strength tests was analyzed to assess the performance and behavior of the test specimen under shear stress. Figure (9) illustrates the Geopolymer brick prisms (P7) while Figure (10) shows the cement brick prisms (P8). Each prism typically consists of three bricks stacked in a staggered arrangement. The prisms were placed in a compression testing apparatus that applied a controlled load. The setup was designed to create a uniform shear stress across the contact surfaces of the bricks. This property is crucial for design considerations and evaluating the structural integrity. The ASTM C 1314 [13], standard and other relevant specifications are commonly referenced this procedure when conducting shear strength tests on masonry specimens.

Fig. 9: Sample of Geopolymer prism (P7)

Fig. 10: Sample of cement prism (P8)

2.8 Walls

Six walls of dimensions 1000×1000×120 mm were divided into two groups were built: group I that consisted of three walls made of Geopolymer bricks mix (3) with Geopolymer mortar while group II consisted of three walls built with cement bricks and cement mortar. Each group consisted of a solid wall, a wall with a window opening of dimensions (250×250) mm, and a wall with a door opening of dimensions (500 × 250) mm, as shown in Figures (11) and (12). The walls of Geopolymer bricks built by Geopolymer mortar and air treated at room temperature. On the other hand, the cement brick walls were built by cement mortar and treated one day after building by spraying the wall with water for 7 days.

Fig. 11: Solid wall, window-opening wall and door opening wall made of Geopolymer brick with Geopolymer mortar.

Fig. 12: Solid wall, window-opening wall and door opening wall made of cement brick with cement mortar.

As shown in Figures 14 and 15, a reinforced concrete beams were used as a base for the walls. Each base was 250× 250 × 1200 mm in size, and was reinforced by 2 Ø 10 upper and lower and stirrups 5 Ø 8/m. After the walls were built, another concrete beam with the same dimensions and reinforcement was cast at the top of the wall which was necessary to ensure a uniform distribution of the applied load on the wall during testing.

3.Results and discussions

3.1 Geopolymer and cement mortars

The compressive strength of the used cement and Geopolymer mortars shown in Table (5) estimated by testing mortar prisms after 28 days. The results are shown in Table (6). the results of both mortars complies with the Egyptian building code is ECP 144 – 2009 [12] for mortar of type (1).

Table 6: Compressive strength of mortar made of Geopolymer and cement.

Mortar type	Average compressive strength (MPa)	Code limits (MPa)
Geopolymer mortar	20.50	15
Cement mortar	15.10	

3.2 Prisms

The tests of prisms were carried out at Helwan University's Mataria laboratory. Cracks gradually appeared during testing of prisms composed of Geopolymer bricks with Geopolymer mortar, as shown in Figures (13,16) and prisms made of cement bricks with cement mortar, as shown in Figures (14,17). Vertical and inclined cracks appeared and increased in number and wide as the applied load increased. On the other hand, a full separation occurred between the bricks at failure in shear prisms in prisms P1, P2, P3, P4, P5, P6, P7and P8, see Figures (25 and 26). The relationships between loads and strains are shown in Figures (18,21,24,27). the initial stiffness of the tested prisms can be computed as the slope of the initial rising part of the load-strain relations. It must be mentioned that the strains were measured and recorded by the LVDT until the applied loads reached about, half the expected ultimate loads to prevent any damage to the LVDT. The recorded strain increased with increasing vertical loads and the appearance of cracks.

Fig. 13: Mode of failure of Geopolymer brick prism under load parallel to the bed joints (P1)

Fig. 14: Mode of failure of cement brick prism under load parallel to the bed joints (P2)

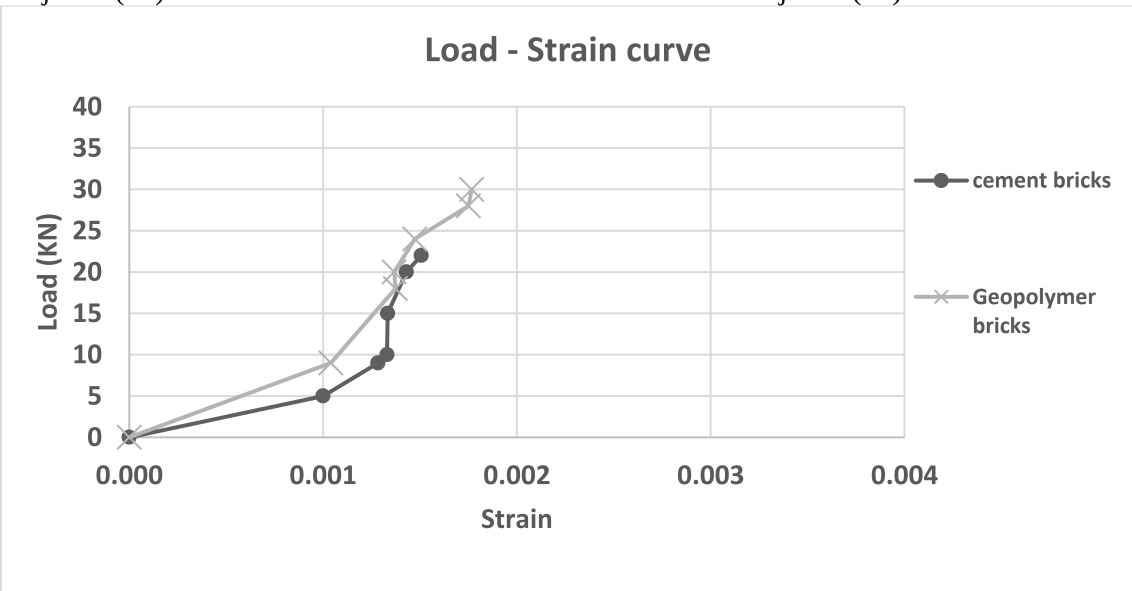


Fig. 15: Load –strain relations for prismsP1and P2 tested under vertical load parallel to the bed joints.

The first crack appeared at a load of 36 KN in Geopolymer bricks, while the first crack appeared in the cement bricks at a load of 27 KN. The ultimate loads were 140 KN and 122 KN for the Geopolymer and cement prisms respectively. The initial modulus of stiffness (K) was 10.5 KN.mm/mm for the Geopolymer bricks and 9 KN.mm/mm for the cement bricks.

Fig. 16: Mode of failure of Geopolymer brick prism under load perpendicular to the bed joints (P3)

Fig. 17: Mode of failure of cement brick prism under load perpendicular to the bed joints(P4)

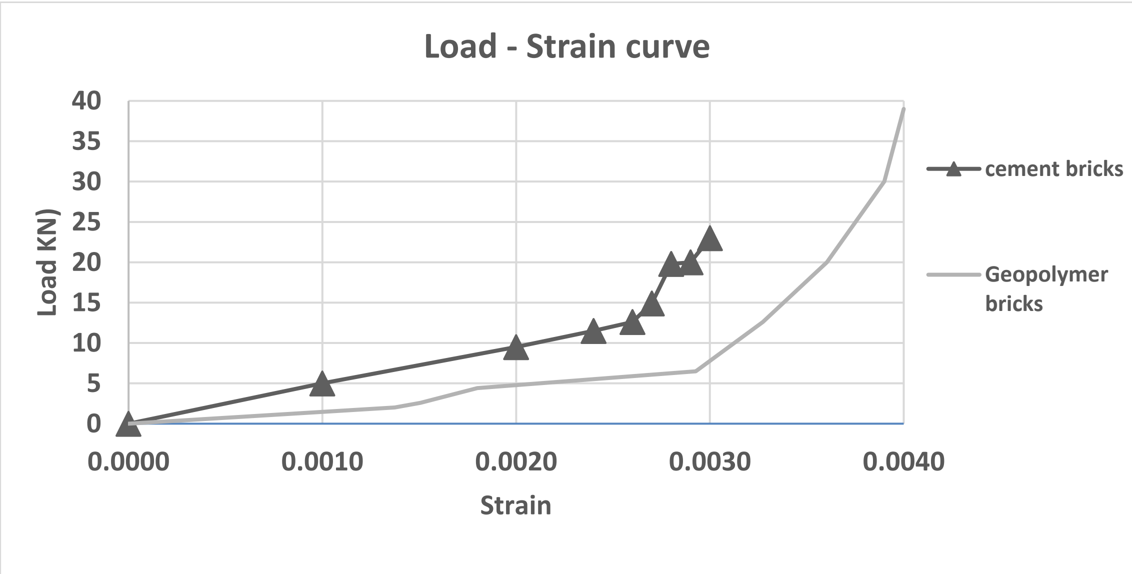


Fig. 18: Load-Strain relations for prisms P3and P4 tested under vertical load perpendicular to the bed joints.

The first crack appeared at a load of 20 KN in Geopolymer concrete prisms P3, while the first crack appeared in the cement bricks P4 at a load of 15 KN. The average ultimate loads were 7 KN and 6 KN for the Geopolymer and cement prisms, respectively. From Figure (18), the initial modulus of stiffness (K) was 15 KN.mm/mm for the Geopolymer brick prisms and 17.3 KN.mm/mm for the cement brick prisms.

Fig. 19: Mode of failure of Geopolymer brick prism under load perpendicular to the bed joints (P5)

Fig. 20: Mode of failure of cement brick prism under load perpendicular to the bed joints (P6)

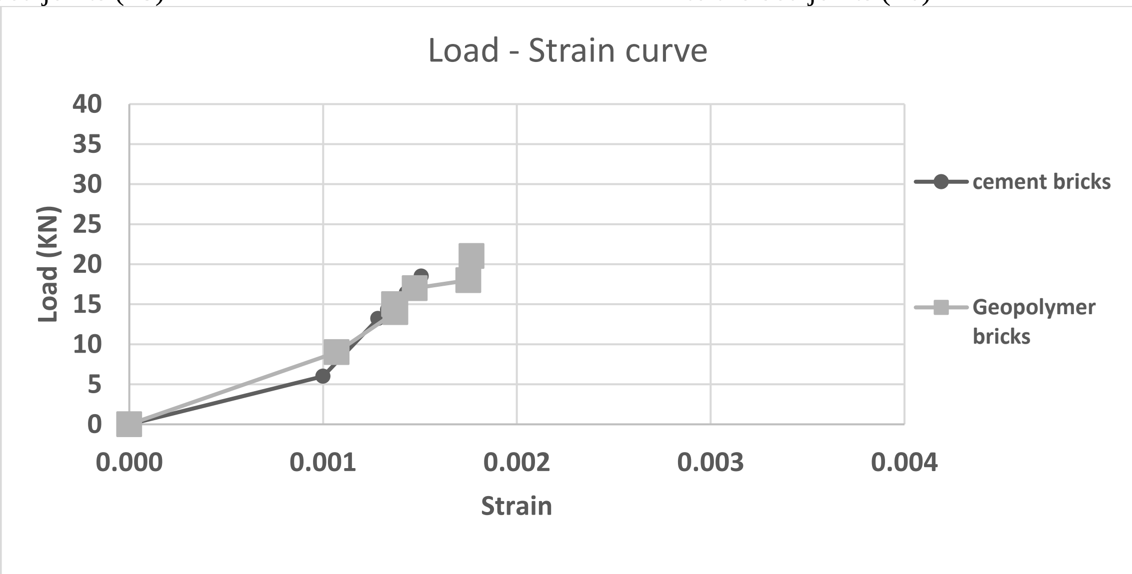


Fig. 21: Load –Strain relations for prisms P5 and P6 tested under vertical load perpendicular to the bed joints.

The first crack in the Geopolymer prism P5 occurred at a load of 43 KN, while the first crack in the cement brick prism P6 appeared at a load of 38 KN. The average ultimate loads for the Geopolymer and cement prisms were 150 KN and 136 KN, respectively. From Figure (21), the initial modulus of stiffness (K) was 10.9 KN.mm/mm for the Geopolymer brick prism and 13.4 KN.mm/mm for the cement brick prism.

Fig. 22: Mode of failure of Geopolymer brick prism under load parallel to the bed joints (P7)

Fig. 23: Mode of failure of cement brick prism under load parallel to the bed joints (P8)

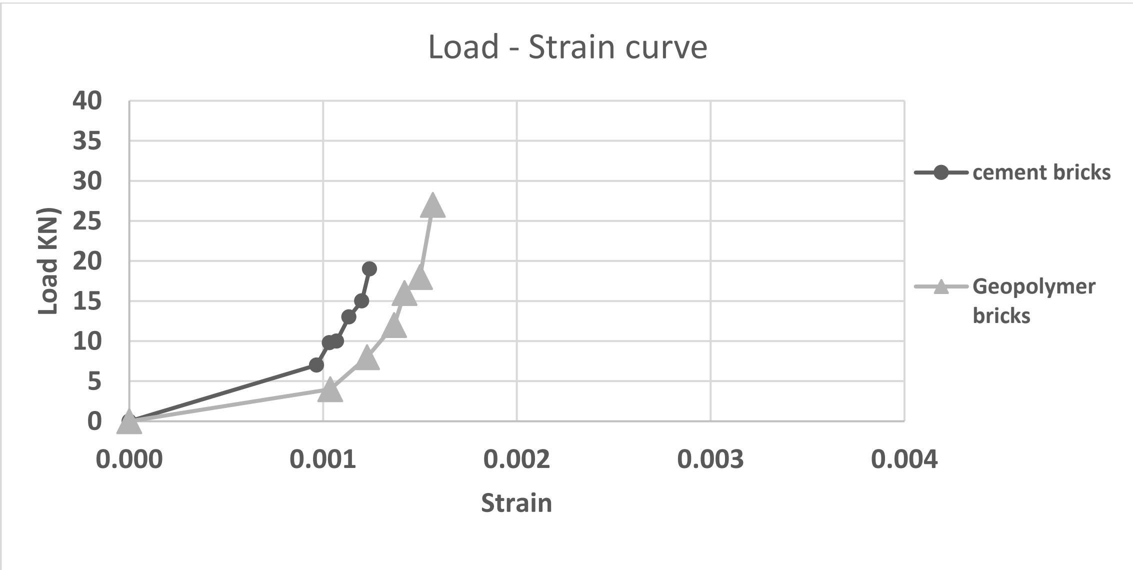


Fig. 24: Load –strain relations for prisms P7and P8 tested under vertical load parallel to the bed joints.

The first crack appeared at a load of 14 KN in the shear Geopolymer concrete brick prism P7, while the cement bricks suddenly separated at the cement mortar. The average ultimate loads were 6 tons for the Geopolymer prisms and 20 KN for the cement brick prism. The initial modulus of stiffness (K) was 8.5 KN.mm/mm for the Geopolymer bricks and 10.59 KN.mm/mm for the cement bricks.

As show, Table (7) that prisms made of Geopolymer bricks demonstrated higher compressive strength than those made of cement bricks by 14.75%, 16.66%, 10.29% and 200% respectively. On the other hand, the initial stiffness in cement bricks were higher than those in Geopolymer bricks by

13.29%, 18.65%, 19.81% respectively, while, for prisms P1 and P2, the initial of stiffness of Geopolymer bricks exceeds that of cement bricks by16.66%. The higher ultimate loads of the Geopolymer brick prisms can be attributed to the higher compressive strength of the Geopolymer concrete bricks and the Geopolymer mortar if compared to the cement bricks and mortar. On the other hand, the Geopolymer brick prisms showed lower initial stiffness values because of the lower modulus of elasticity of the Geopolymer concrete. Mostafa, M (2018) as mentioned in Modulus of elasticity of Geopolymer concrete represents approximately (40 %) -as average- from modulus of elasticity of conventional concrete [14].

Table 7: Max ultimate loads and initial modules of stiffness prisms.

samples	P1(G)	P2(C)	P3(G)	P4(C)	P5(G)	P6(C)	P7(G)	P8(C)
P_{ULT} (KN)	140	122	70	60	150	136	60	20
Initial stiffness(K) (KN.mm/mm)	10.5	9	15	17.3	10.9	13.4	8.5	10.6

3.3. Walls

3.3.1. Failure loads

According to the results, in general, it was found that the ultimate loads of solid walls were higher than those of walls with door or window openings. The presence of openings in the walls weakened them. On the other hand, as shown in Table (8), and Figure (25), the walls made of Geopolymer bricks demonstrated higher fracture loads if compared to the corresponding cement brick walls. Such result can ensure that the Geopolymer brick loads may be effective to use in wall bearing structures. In addition, it can be noted that the reduction in the ultimate load due to the presence of openings in Geopolymer concrete brick walls were lower than cement brick walls. The reductions were 13.33% and 20.00% in Geopolymer concrete brick walls of window and door openings, respectively, while those reductions were 34.02% and 36.84%, respectively, in cement brick walls.

Table 8: The failure load for all walls

Wall no.	Type wall	Failure load (KN)
W1	Geopolymer concrete brick solid wall	300
W2	Cement concrete brick solid wall	260

W3	Geopolymer concrete brick wall with window	260
W4	Cement concrete brick wall with window	194
W5	Geopolymer concrete brick wall with door	240
W6	Cement concrete brick wall with door	190

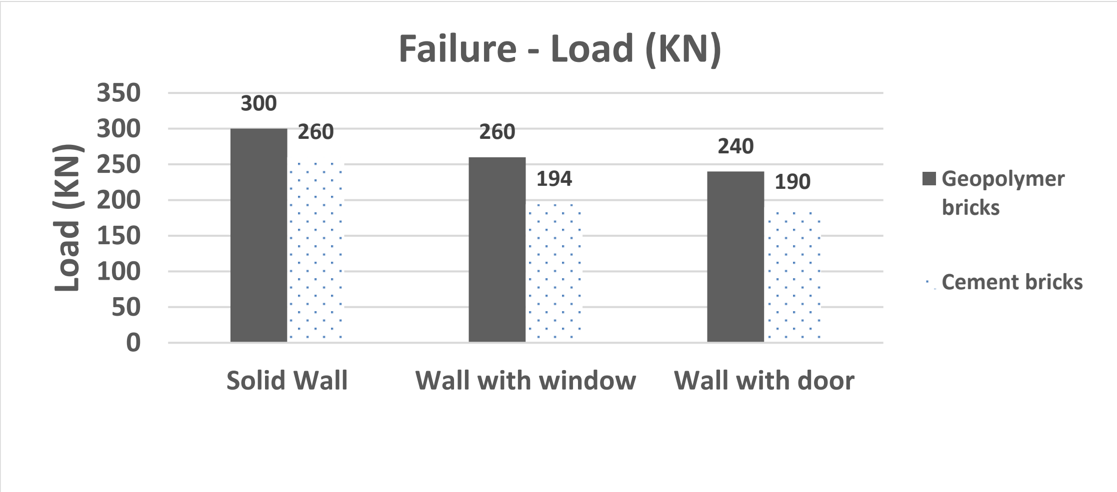


Fig. 25: Comparison of the failure load of all walls.

3.3.2. Crack Patterns and Failure Shapes

3.3.2.1 Solid walls

Fig. 26: Crack pattern and failure shape of Geopolymer brick solid wall W1.

Fig. 27: Crack pattern and failure shape of cement brick solid wall W2.

As shown in the previous figures, upon overloading ,inclined cracks began to gradually appeared in wall W1 at 190 KN and widened until the maximum breaking load reached 300 KN. Near to the ultimate load, some parts of the bricks fallen at the middle part of the tested wall, see Figure (26). On the other hand, cracks in the solid cement brick wall W2 began to gradually appeared at 190 KN and widened until the maximum breaking load reached 260 KN. Also, near to the ultimate load, some bricks of upper part of the tested wall felled, see Figure (27).

3.3.2.2 Walls with windows openings

Fig. 28: Failure shape of Geopolymer brick wall with Window W3.

Fig. 29: Crack pattern and failure shape of Cement brick wall with Window W4.

As shown in Figures (28and 29), upon overloading, the inclined cracks which appeared at the opening corner began to gradually widened window in wall W3 at 180 KN and 150 KN tons in W4. At the failure loads, collapse occurred suddenly in W3 and gradually in W4.

3.3.2.3 Walls with doors openings

Fig. 30: Crack pattern and failure shape of Geopolymer brick wall with door W5.

Fig. 31: Failure shape of cement brick wall with door W6.

As shown in the previous Figures (30 and 31), upon overloading ,vertical cracks appeared in wall W5 at 180 KN and 150 KN in wall W6. Near to the ultimate loads, large parts from bricks besides the door opening of the tested walls collapsed.

3.3.4 Load – strain relationships

Vertical strains were measured versus the applied loads of the tested walls up to about 60% of the ultimate loads to prevent damages may occurred in the LVDTs. The load -strain Relationships are drawn for all tested walls as illustrated in the following sub-sections.

3.3.4.1 Load – strain for solid wall

Figure (32) shows the load -strain relationships of the solid Geopolymer and cement walls W1and W2. The initial stiffness can be computed as the average slope of the relations up to about 30% of ultimate loads.

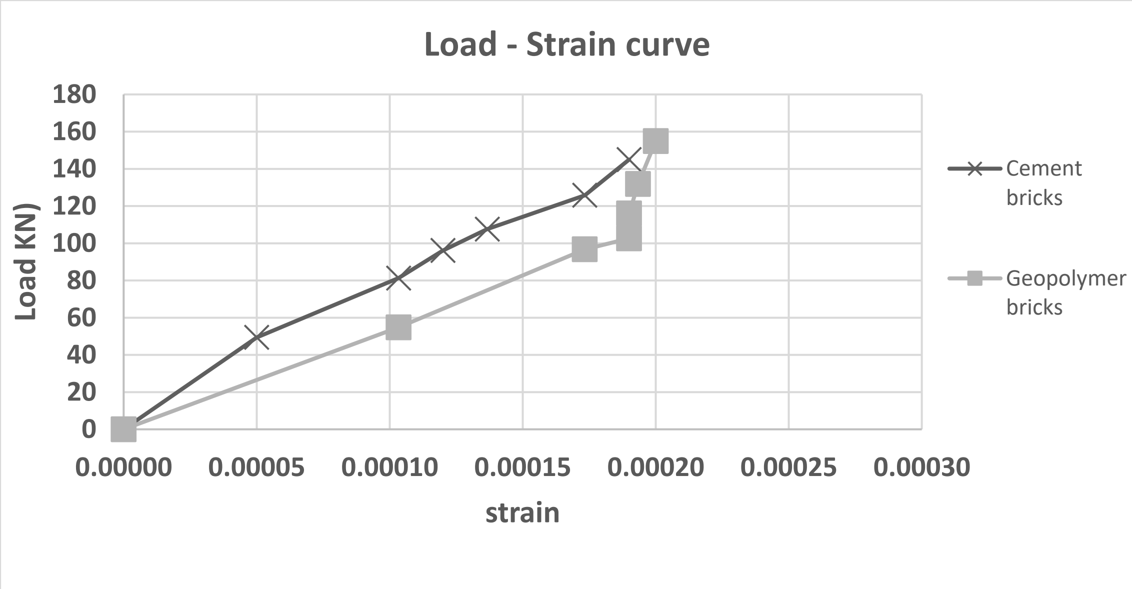


Fig. 32: Load – strain relationships for solid walls.

It is evident from Figure (32) that the initial stiffness in the solid wall made of cement brick was 56 KN.mm/mm, while it was 32 KN.mm/mm for the Geopolymer brick wall. Therefore, the stiffness of cement brick wall was 42.85% higher than the corresponding Geopolymer brick wall.

3.4.3.2 Load – strain for wall with window

Figure (33) shows the load -strain relationships of the Geopolymer and cement walls W3 and W4. The initial stiffness can be computed as the average slope of the relations up to about 30% of ultimate loads.

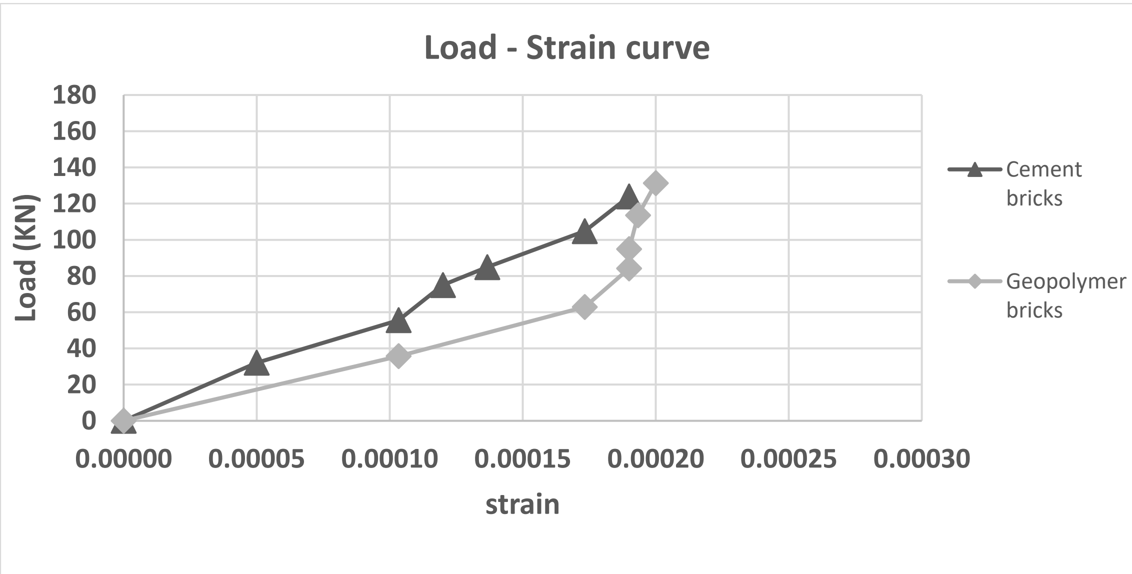


Fig. 33: Load – strain relationships for walls with window.

It is evident from Figure (33) that the initial stiffness in wall with window made of cement brick was 18 KN.mm/mm, while it was 10.0 KN.mm/mm for Geopolymer brick walls. Therefore, the initial stiffness of the cement brick wall was 44.44% higher than the corresponding Geopolymer brick wall.

3.4.3.3 Load – strain for wall with door

Figure (34) showed the load -strain relationships of the Geopolymer and cement walls W5 and W6. The initial stiffness can be computed as the average slope of the relations up to about 30% of ultimate loads.

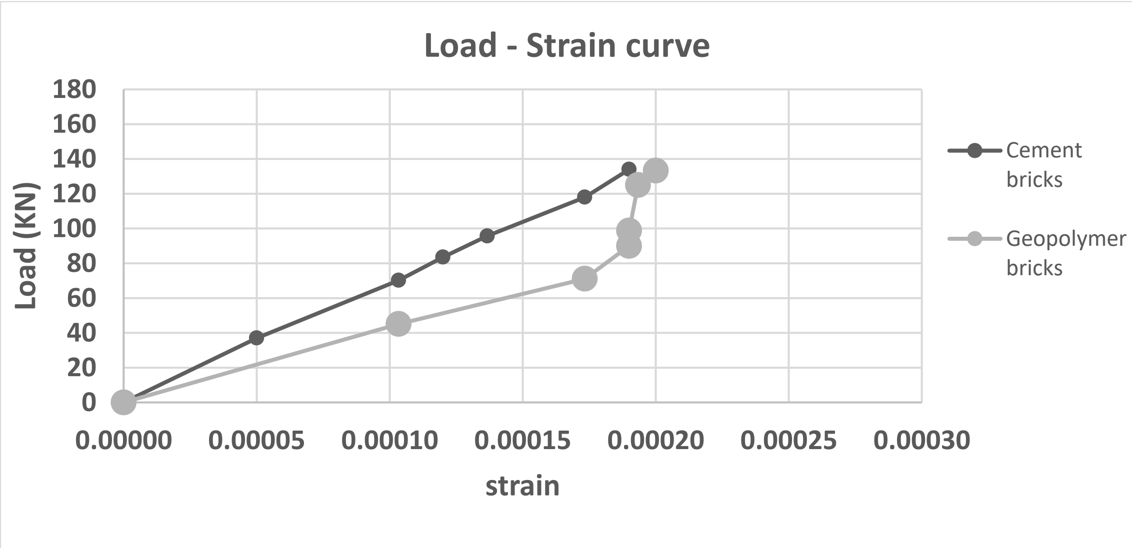


Fig. 34: Load – strain relationships for walls with door.

It is evident from Figure (34) that the initial stiffness in wall with door made of cement brick walls was 30 KN.mm/mm, while it was 19 KN.mm/mm for Geopolymer brick wall. I.e., the initial stiffness of the cement bricks wall was 36.66% higher than the corresponding Geopolymer brick wall.

3.4.3.4 Effect of presence of opening in cement walls on the load –strain relationship

Figure (35) illustrates the effect of the presence of door or window openings on the load –strain relation of the cement brick walls. The figure shows that the initial stiffness's for the solid wall, the wall with a door opening, and the wall with a window opening, were 56 ,30 and 18 KN.mm\mm, respectively. The solid cement brick wall exhibited an initial stiffness 46.42% higher than that of the wall with a door opening and 67.85% higher than that of the wall with a window opening.

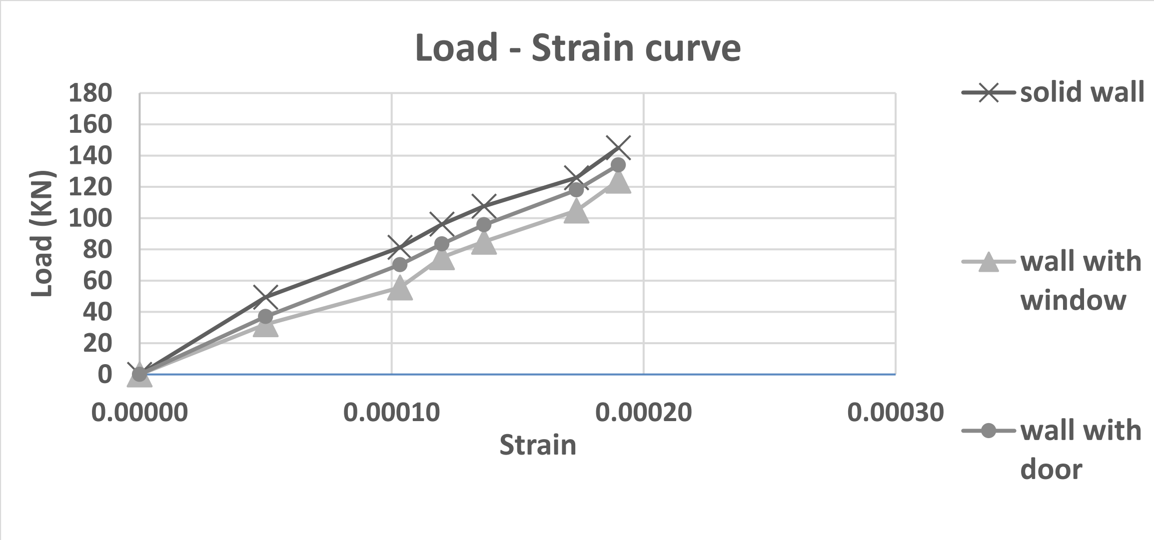


Fig. 35: Load – strain relationships for cement walls.

3.4.3.5 Effect of presence of opening in geopolymer walls on the load –strain relationship

Figure (36) illustrates the effect of the presence of door or window openings on the load –strain relationships of Geopolymer brick walls. The figure shows that the initial stiffness's for the solid wall, the wall with a door opening, and the wall with a window opening, were 32, 19 KN, and 10 KN.mm\mm, respectively. The solid Geopolymer brick wall exhibited an initial stiffness that is 40.62% higher than that of the wall with a door opening and 68.75% higher than those of the wall with a window opening are. The above results mean that the presence of window openings caused more reductions in the initial stiffness values of the tested cement and Geopolymer bricks walls. This may be attributed to the position of the window openings, which were in the middle of the walls. This position may cause more reductions in the measured initial stiffness the tested walls.

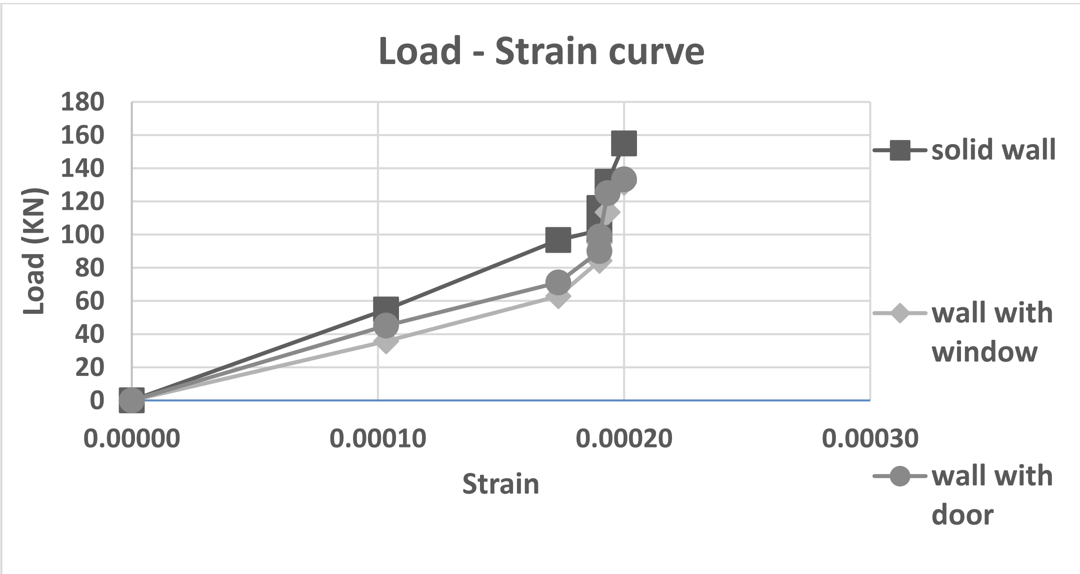


Fig. 36: Load – strain relationships for geopolymer walls.

5. Conclusion

1. Manufacturing wall bearing bricks similar to cement bricks from Geopolymer concrete had been successfully applied in a brick factory, which can open new horizons for brick industry without using cement.
2. Prisms made of Geopolymer bricks demonstrated higher compressive strength than those made of cement bricks. The increase in the prism strengths ranged from 10.30% to 200% according to their shapes and types.
3. The initial stiffness for Geopolymer brick prisms was lower than those of cement brick prisms by 13.30% to 19.80%. This can be attributed to the lower modules of elasticity of the Geopolymer concrete.
4. The compressive strength of the solid Geopolymer brick wall provided 15.40% higher than cement brick wall.
5. The solid Geopolymer brick wall had a lower initial stiffness than the cement brick wall by 42.85%. Such results mean that the Geopolymer wall was stronger under load but may deform more than the cement brick wall because of the lower value of modules of elasticity of the Geopolymer concrete.
6. The compressive strength of the wall with window and made of Geopolymer brick wall provided 34.00% higher than cement brick wall.
7. The wall with window and made of Geopolymer bricks had a lower initial stiffness than the cement brick wall by 44.44%.
8. The compressive strength of the wall with door and made of Geopolymer brick wall provided 26.30% higher than cement brick wall.
9. The wall with door and made of Geopolymer bricks had a lower initial stiffness than the cement brick wall by 36.66%.
10. The solid cement brick wall showed a stiffness of 46.40% higher than that of the wall with a door opening and 67.85% higher than that of the wall with a window opening.
11. The solid Geopolymer brick wall showed a stiffness of 40.62% higher than that of the wall with a door opening and 68.75% higher than that of the wall with a window opening.
12. The presence of window openings caused more reductions in the initial stiffness values of the tested cement and Geopolymer brick walls. This may be attributed to the position of the window openings, which were in the middle of the walls. This position may cause more reductions in the measured initial stiffness the tested walls.
13. The Geopolymer bricks saved the bricks cost by 26.70% when compared to cement bricks.

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